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CONTAINMENT OF BURIED NUCLEAR EXPLOSIONS

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Abstract

The mechanisms that lead to a release of radioactive contaminants (venting) are discussed.

The processes that appear to be of primary concern in dynamic venting are (1) uncontrolled cavity growth toward the free surface, (2) energy flow through large diameter openings, and (3) upward displacement of cavity gases during chimney formation. For Plowshare experiments, the first and the third become the controlling mechanisms for dynamic venting.

Logically derived models based on a fundamental physical understanding of these mechanisms are presented. These models provide an initial step toward developing criteria which assure that dynamic venting through the ground will not occur.

Introduction

In order to constructively use nuclear explosives for civil and industrial purposes, it is fundamental to reduce radiological hazards to acceptable levels. One means of essentially eliminating atmospheric contamination is to bury the explosion deeply so that the radioactive materials produced are contained below the surface of the ground. This practice is compatible with underground engineering applications such as gas-well stimulation, in situ leaching, and numerous others. The central question is how deep must a given event be buried to insure that the event is contained.

At this time the burial criterion used to insure containment in Plowshare underground application experiments is an empirical recipe (Fig. 1). This criterion was derived from venting experience in the environments encountered at the Nevada Test Site (NTS). The validity of the recipe can be questioned when it is extended to greater yields or to geologic environments different from those which have been experienced. For this reason a recently established objective of Plowshare research is to replace this empiricism with logically derived models which are based on a fundamental physical understanding of the phenomenon. The direction of this research is to identify venting mechanisms, to evaluate flow conditions along paths which exist in the vicinity of detonation as a function of time, and finally to evolve criteria to prevent dynamic venting to the atmosphere. This report describes briefly the state of this investigation and the understanding achieved at this time.

A distinction should be made between "venting mechanism" and "burial criterion." In this report a venting mechanism refers to a genetic process occurring as a

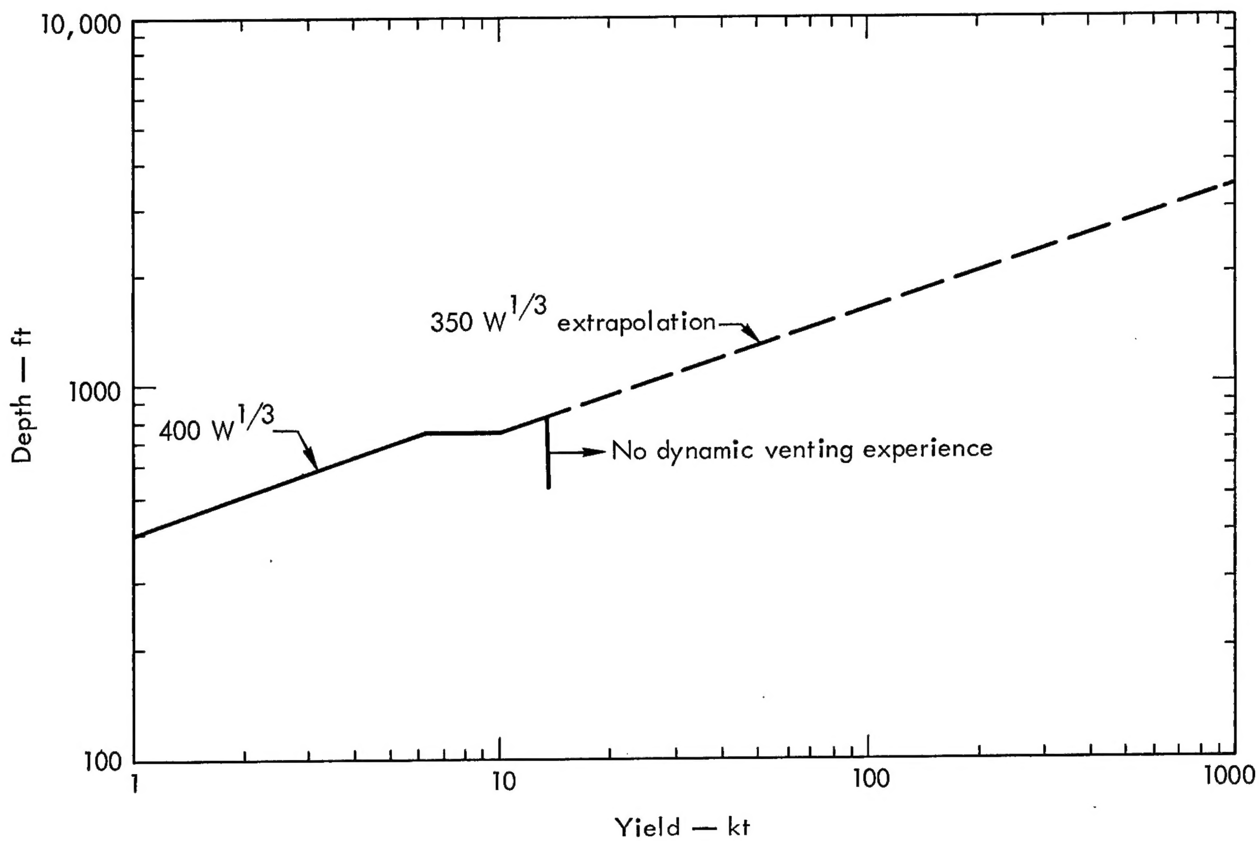

Fig. 1. Empirical containment criteria developed from NTS experience.

result of a nuclear explosion which can eventually lead to the release of radioactive contaminants at the ground surface. A burial criterion provides a relationship of depth of burial vs yield below which venting by a given mechanism can be predicted not to occur.

Venting Mechanisms

It is convenient to discuss venting mechanisms in two general categories: (1) prompt-venting mechanisms, those which operate prior to chimney formation, and (2) late-time mechanisms, those which operate during and following chimney formation. The first category obviously includes the mechanics of cratering. In these events, the burial depth is not sufficient for the expanding cavity gases to reach a point of dynamic equilibrium with the containing environment. The cavity continues to grow by "gas acceleration" until venting occurs through tensile cracks developed from spherical divergence of the mound surface. The term "gas acceleration" refers to the asymmetrical growth of an explosion-produced cavity under the influences of returning rarefaction waves from the earth's surface (see Fig. 2). If the burial depth is sufficient for the returning

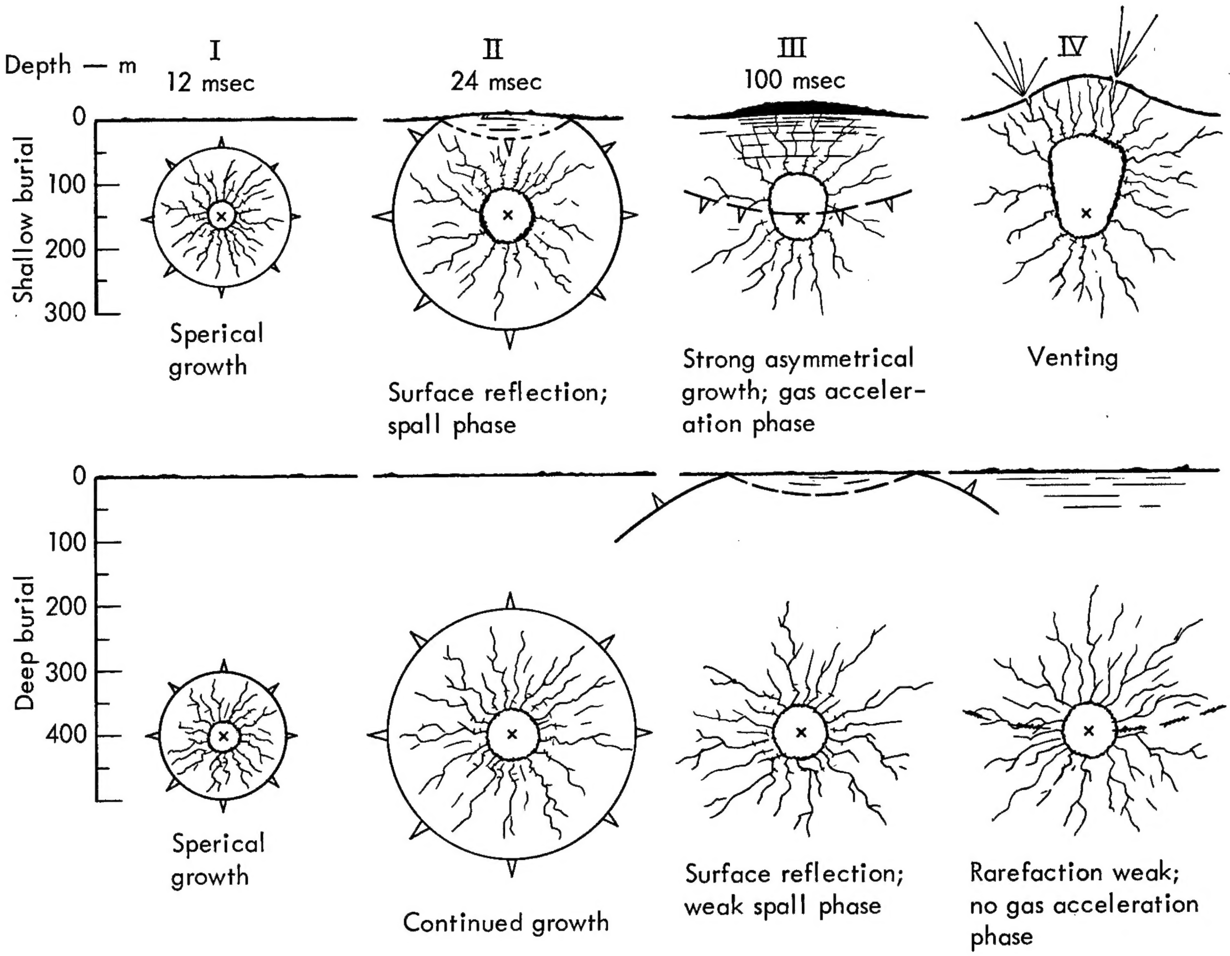

Fig. 2. Effect of depth on buried explosions.

rarefactions to be largely attenuated, then no significant gas acceleration phase of cavity growth will occur. At this depth complete containment with respect to cavity growth is achieved, since the cavity does not sense the existence of the surface.

In the case in which containment with respect to cavity growth is achieved, the resulting structure is essentially a cavity filled with rock gas surrounded by a region of failed and compacted materials, all existing in a lithostatic stress field. The pressure in the cavity at maximum growth is somewhat greater than overburden because of the strength of the overlying geologic materials.[1] The venting mechanisms that can operate during and following the formation of this quasi-stable structure involve mass or energy transport along paths existing through the shock-deformed media. These mechanisms are (1) flow through large continuous openings, (2) permeation through interstitial openings, and (3) a combination of these processes. An evaluation of venting by these mechanisms requires knowledge of the types of openings which may exist in the regions surrounding the cavity as a function of time.

Late-time venting mechanisms are closely associated with cavity collapse

and chimney formation (Fig. 3). These mechanisms are displacement, permeation, diffusion, and percolation. As collapse progresses upward in the chimney formation process, the volume of rubble falling into the cavity displaces an equal volume of gas. The propagation rate of the cavity gas upward is the rate of collapse. Chimney collapse rates of approximately 30 m/sec have been observed in alluvium.[2] It should be noted here that there will always be a finite rate associated with collapse. Collapse of the entire structure cannot be instantaneous since the stress field must have time to adjust to the new structures being created.

In the case where a subsidence crater is created, dynamic venting can occur by the displacement mechanism provided the cavity gases being displaced have not cooled and condensed in the time required for the collapse to propagate to the surface. In the case where collapse does not reach the surface, the mechanisms that could lead to the propagation of contaminants above the height of the chimney are permeation (provided there is still a pressure differential), gas diffusion, and percolation. Gas diffusion refers to processes by which contaminants can propagate under chemical, thermal, or gravity potentials. Percolation refers to movement of contaminants with ground water. Gas diffusion could be an important venting mechanism if the event involved the generation of large quantities of noncondensable gases such as would be produced by nuclear explosions in calcareous or carbonaceous materials. This type of venting may not be dynamic, but could result in considerable seepage at the surface over a long period of time. Though of interest from the standpoint of

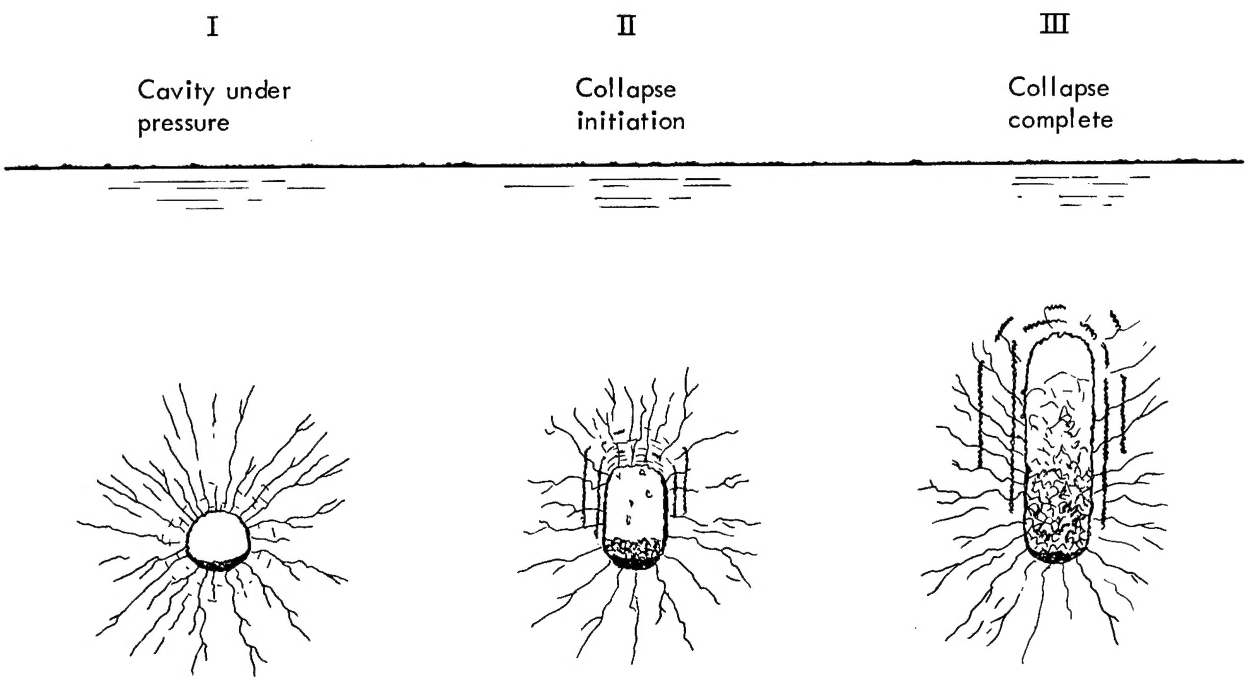

Fig. 3. Chimney formation.

local safety considerations, these mechanisms are not of interest from the standpoint of dynamic venting.

To summarize, the venting mechanisms which can result in the dynamic release of contaminants at the surface appear to be (1) the gas acceleration phase of cavity growth, (2) energy flow through continuous openings, (3) prompt permeation through interstitial openings, (4) displacement during collapse and late-time permeation through the region above the chimney, and (5) combinations of these processes. Each of these mechanisms requires further discussion and evaluation.

Gas Acceleration

Gas acceleration has been described as the genetic process by which the cavity grows asymmetrically toward the surface. The fact that this process may occur in a particular event does not necessarily mean that a dynamic vent will also occur. Venting by this process appears to be dependent upon the development of cracks created by spherical divergence of the ground surface propagating into the cavity region. The critical point where venting occurs in this process cannot be predicted from existing theoretical or empirical models. With our current knowledge of explosive mechanics, however, it is possible to define the depth corresponding to a given yield and geologic environment below which no significant gas acceleration phase of cavity growth occurs. At that depth or below, containment of venting by this mechanism is achieved. Existing computer codes which incorporate explosive mechanics and appropriate material descriptions can predict these conditions.

The codes referred to are SOC and Tensor, which are one- and two-dimensional Lagrangian stress wave codes that use the actual material properties found in the shot environment. The material properties[3] (equations of state) used to calculate a particular event are obtained from a detailed field and laboratory examination of the shot media.[3]

The field examination is composed primarily of a logging program designed to obtain:

1. Density logs over the entire hole
2. Elastic velocity logs
3. Complete lithologic descriptions

These logs provide (1) valuable information about the index properties of the media, and (2) a basis for the selection of representative samples for detailed laboratory testing. The following are the laboratory tests necessary to describe material behavior in the stress environments resulting from buried nuclear detonations:

1. Hydrostatic compressibility test up to 40 kbar
   a. Loading and unloading curves for the consolidated materials
   b. Unloading curves for the brittle-failed material
2. Strength measurements
   a. Triaxial tests (maximum and residual strength)
   b. Tensile strength tests
   c. Hugoniot elastic limit
3. Chemical composition near shot point
4. High-stress Hugoniot compressibility data for those rocks near the shot point.

With the results of this program, reasonable descriptions of material

behavior can be obtained. These descriptions (both geometry and material properties) and the energy yield of the explosion are input to the code. The output is a microsecond-by-microsecond account of energy state, pressure, density, velocity, and position for every element making up the geometric matrix. From these quantities the shock position, the cavity growth, and the extent of material failure can be obtained directly. Figures 4 and 5 show the time history for shallow and deeply buried nuclear events as calculated by SOC. These histories are equivalent to the pictorial representation shown in Fig. 2.

The use of this numerical technique to predict wave propagation and shock effects, such as cavity growth and extent of material failure, has been adequately demonstrated in nuclear experiments in a wide variety of geologic environments by comparison of observed shock effects to the corresponding calculated values.[3,4,5] This experience includes accurate prediction of the effects of explosives in ten separate experiments involving eight different rock types. Further, this experience includes prediction of cratering events as well as deeply contained events. A fundamental achievement is the demonstrated ability to predict realistic millisecond-by-millisecond accounts of shock propagation, mound and cavity growth, and related phenomena as a function of yield, depth, and material properties using a first principle model. Moreover, the SOC and Tensor codes make possible meaningful model and parameter studies that extend our knowledge of shock phenomenon beyond field experience.

Figure 6 shows the results of a SOC parameter study using the Lewis shale equation-of-state (Gasbuggy Event).[6] In this study the material description and depth of burial were held constant, while the yield was increased in a series of

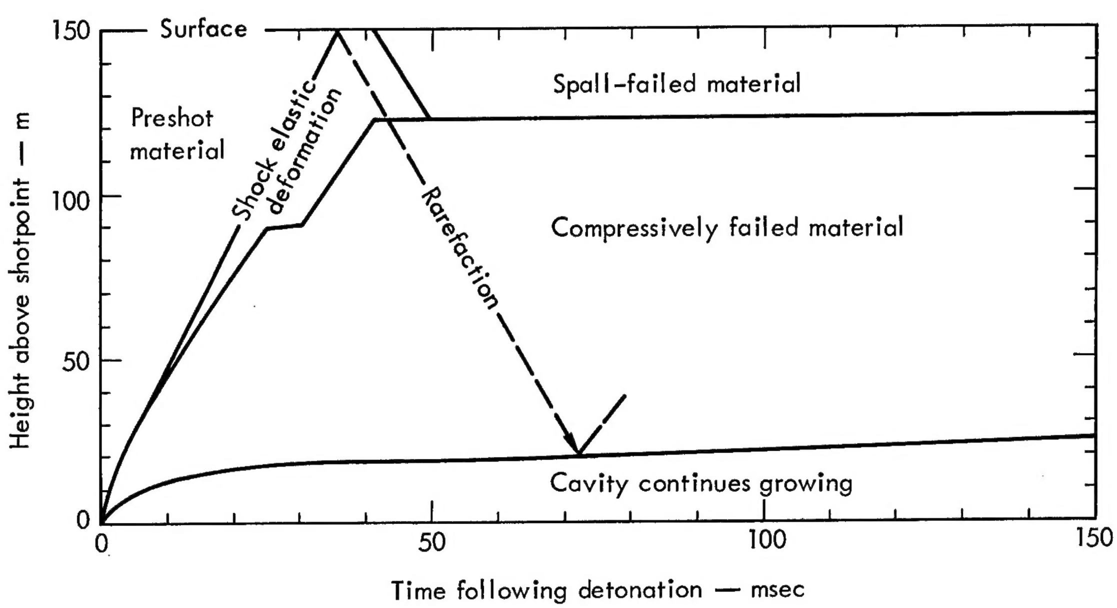

Fig. 4. History of near-surface event as calculated by SOC (depth, 150 m; material, Lewis shale; yield, 10 kt; after Rapp, 1968).

calculations. The figure shows final cavity radius as a function of yield. Note that in the lower yield range the final cavity radius is related to yield by energy scaling ($R_c = CW^{1/3}$). In the calculations made in this lower range of yields, the returning rarefaction from the free surface was attenuated and had no effect on

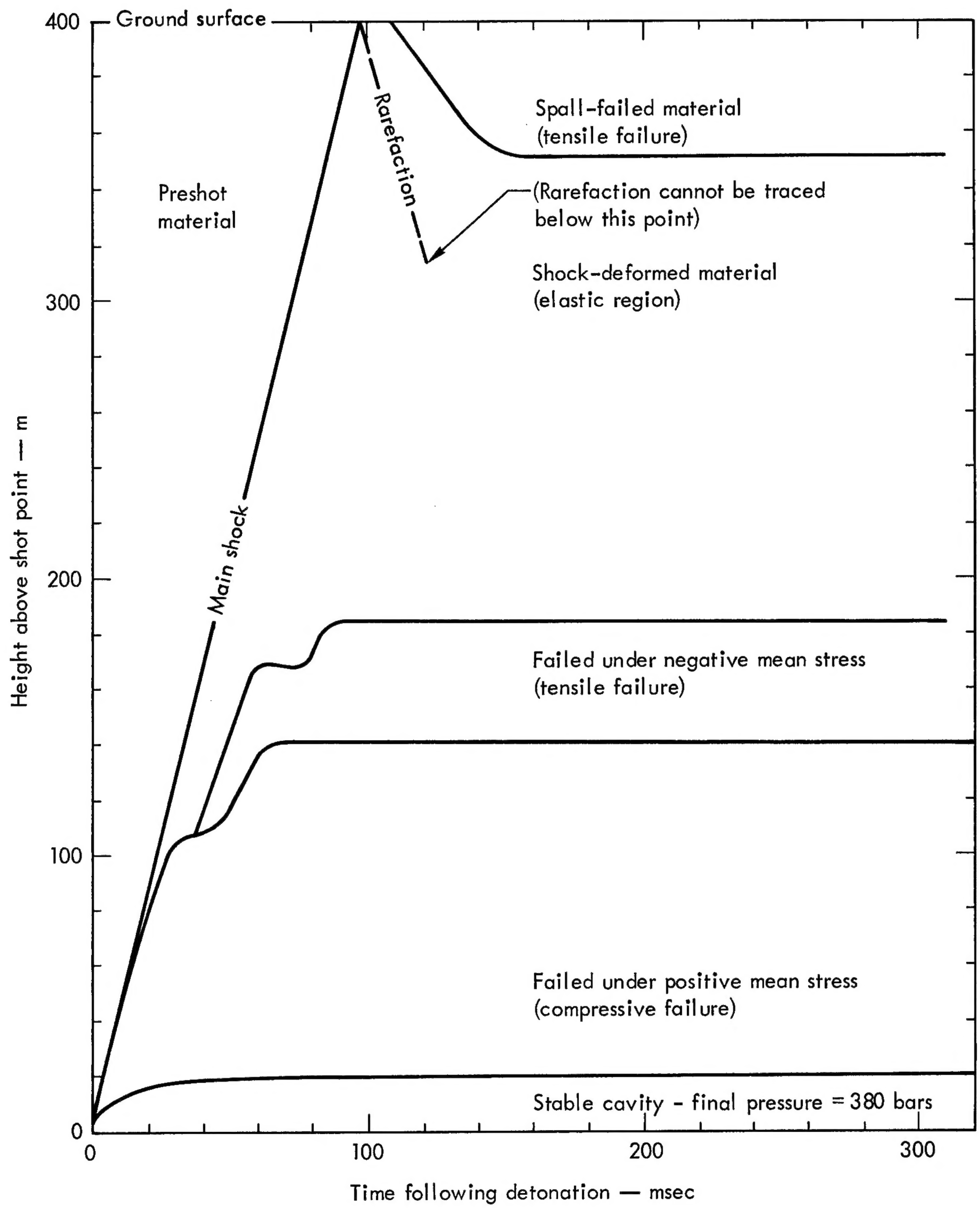

Fig. 5. History of deeply buried event as calculated by SOC (depth, 400 m; material, Lewis shale; yield, 10 kt; after Rapp, 1968).

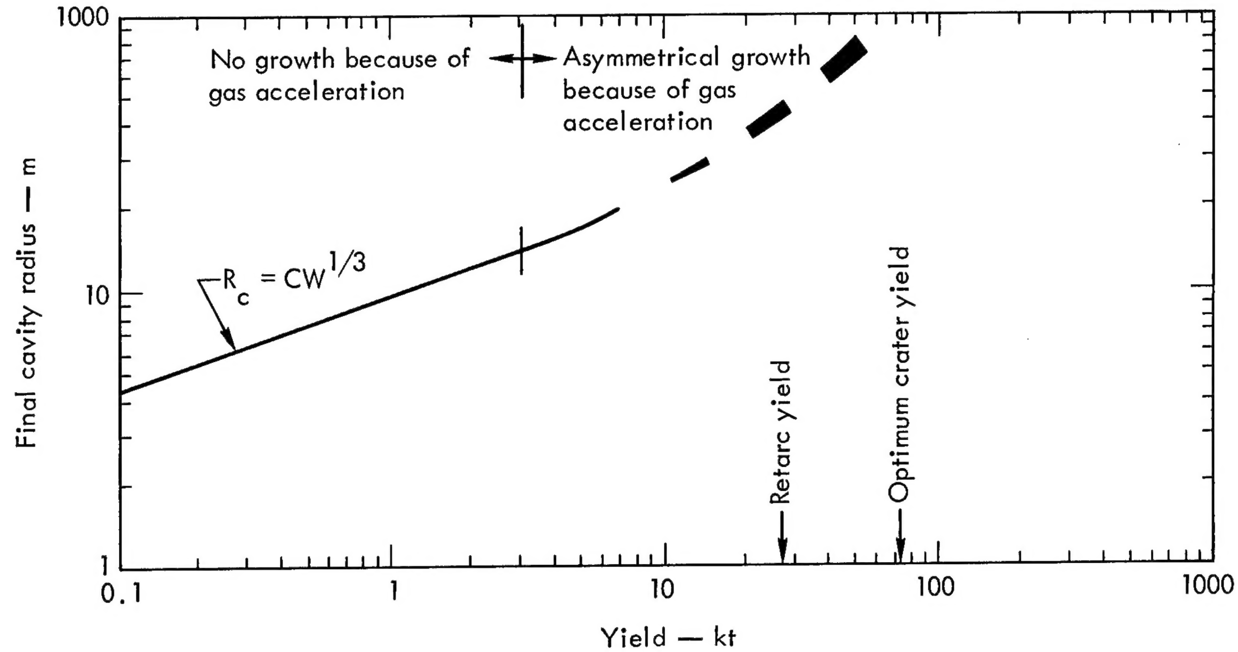

Fig. 6. Results of SOC parameter study in Lewis shale (constant depth of burial, 150 m).

cavity growth. The calculations show, however, that above 3 kt in this environment, a boost in cavity growth would occur because of gas acceleration. This boost in growth becomes increasingly severe as the yield is increased. It is not possible with this model to predict the maximum yield for this particular environment where containment of venting processes because of gas acceleration can still be achieved. However, one can predict that containment will be achieved for yields below 3 kt, since gas acceleration processes do not operate. Figure 7 shows the results of several series of calculations run at various depths of burial. The yield corresponding to a given depth of burial where R_c begins to deviate from a $R_c = CW^{1/3}$ relationship defines a point that can be used in a depth of burial vs yield criterion to prevent gas acceleration processes from operating. Figure 8 shows the resulting burial criterion for this material.

Parameter studies using numerical descriptions of Hardhat granite[5] and Pictured-Cliffs sandstone[6] show that the depth vs yield relationship where gas acceleration becomes effective is extremely dependent upon the material. Figure 9 shows a comparison of this relationship for the three materials studied to date.

The following is a valid question at this point: How conservative is this proposed containment model in defining a depth to prevent venting by gas acceleration processes? Three events have been fired in granite at depths less than would be allowed by the proposed gas acceleration criteria. These events were Hardhat, Shoal, and Piledriver.[7,8] In each of the events containment of dynamic venting by all processes was achieved. Figure 10 shows the results of a series of calculations made with the numerical description for Hardhat granite compared to measured final cavity radii. It appears from the calculation that each of the

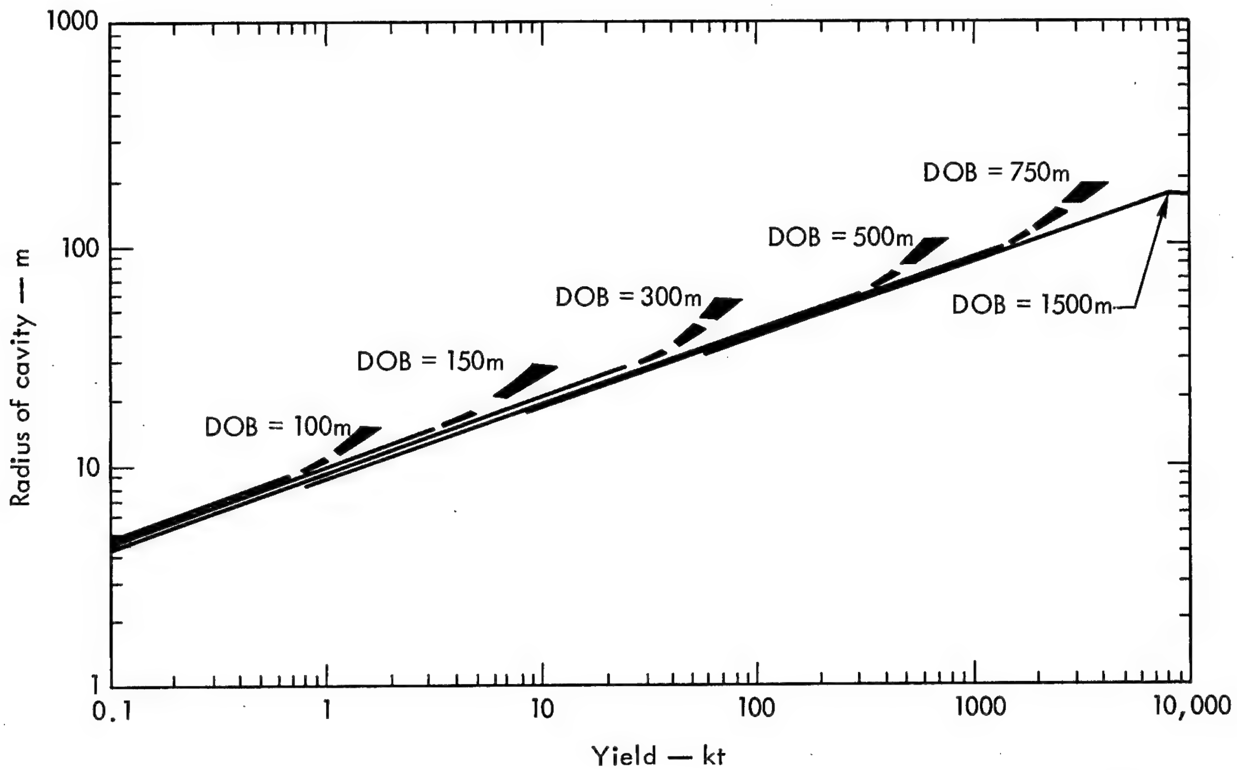

Fig. 7. Results of several series of calculations at various depths of burial (SOC parameter study in Lewis shale).

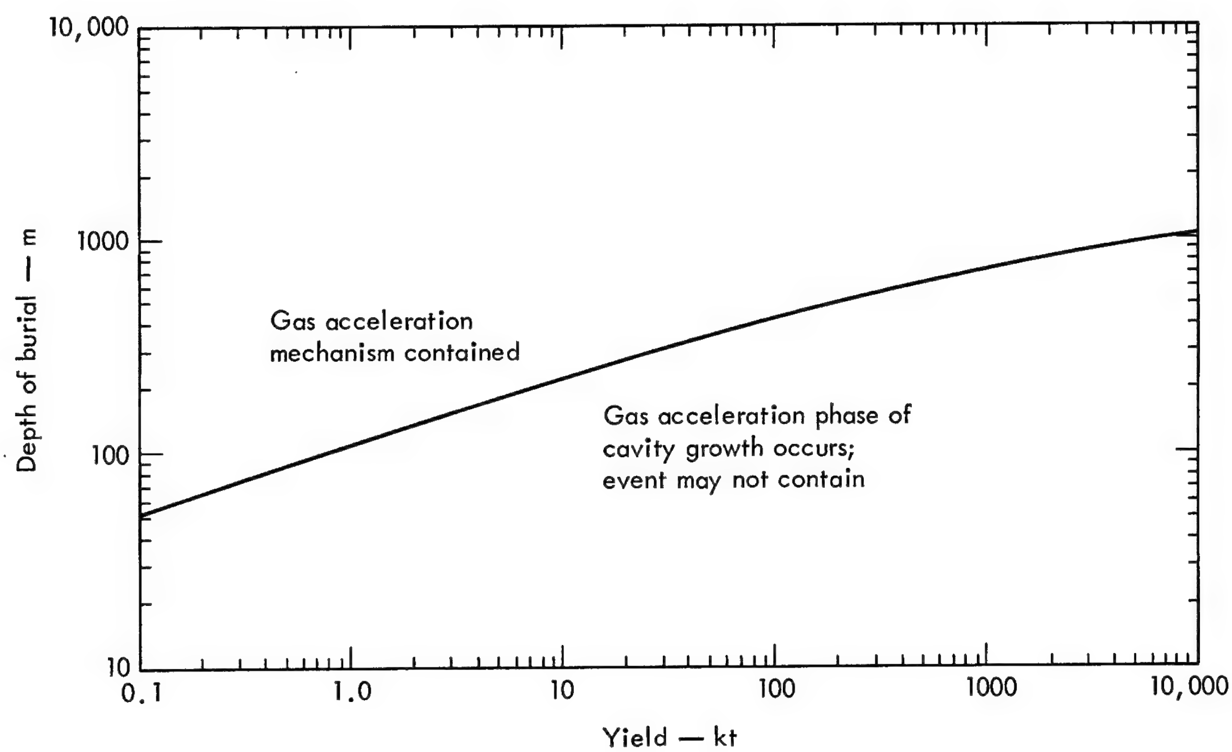

Fig. 8. Burial criterion (gas acceleration in Lewis shale).

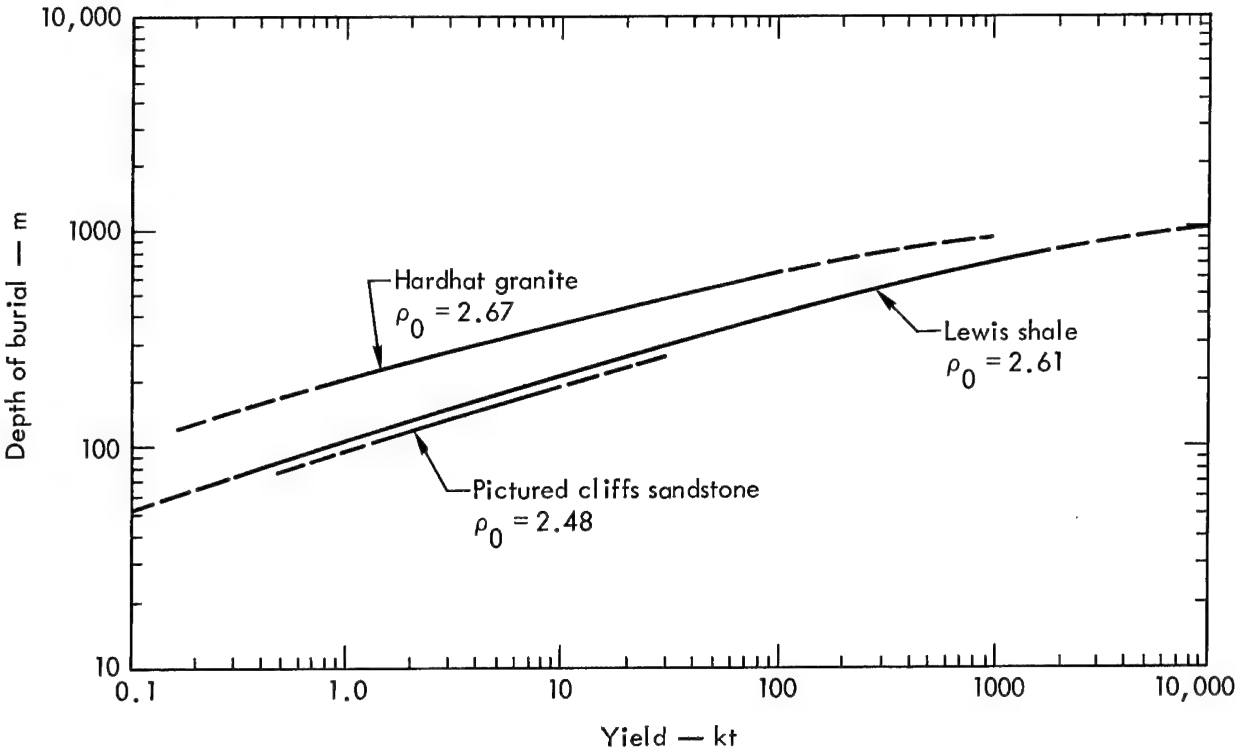

Fig. 9. Comparison of depth of burial vs yield relationship for three materials showing effect of gas acceleration.

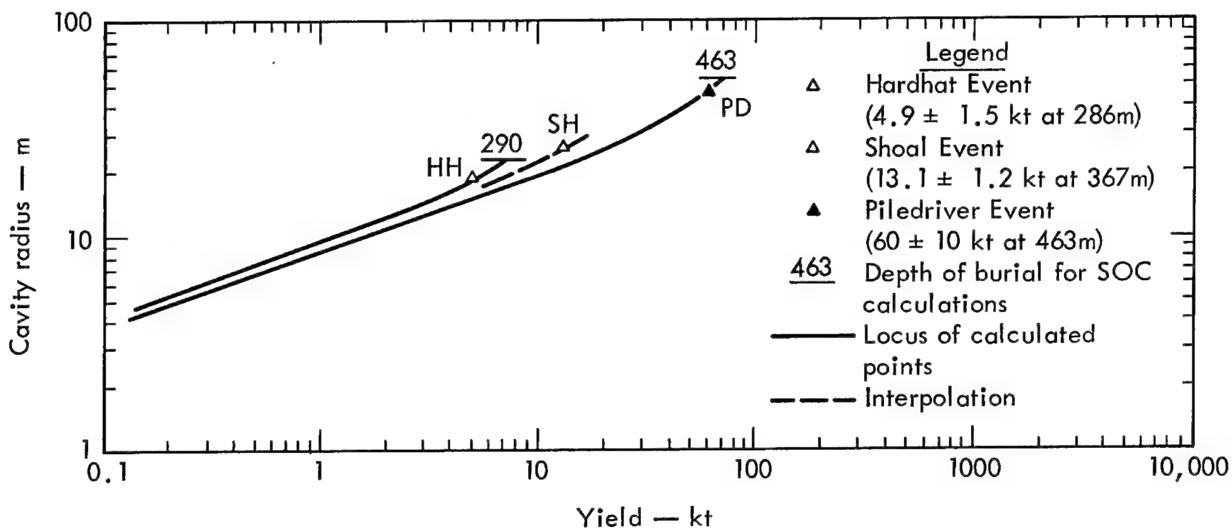

Fig. 10. Comparison of SOC parameter study and measured cavity radii for three events in granite at various depths of burial.

three events experienced some gas acceleration in cavity growth,[5] yet containment was achieved. Based on this analysis, the criterion proposed to prevent venting by gas acceleration processes is conservative, certainly more conservative than our experience in granite.

Energy Flow Through Continuous Openings

This mechanism is associated principally with man-made openings (cable openings, etc), since continuous openings occur only rarely in nature. A criterion to prevent venting by this process should be based only on the degree of confidence that can be allowed in the design and construction of stemming and closure systems. With regard to this venting process, a burial criterion has no meaning except to provide physically the space to install closure systems. The prevention of venting by this mechanism is largely dependent upon established design criteria.

Permeation Through Interstitial Openings

Permeation refers to mass flow through small tortuous openings where the potential for flow is a pressure differential. In order to evaluate venting by this mechanism an examination of the paths through which this process may operate must be made. The paths considered are pore connections, preexisting cracks and faults, shock-induced cracks, and late-time tensile openings.

Permeation from a standing cavity under pressure might take place through natural pore connections or through crack porosity. An examination of the flow rates and transit times that can be expected if permeation occurs only through these connections allows an evaluation of this path as a likely prompt-venting path. The POROS code (one-dimensional flow with heat loss)[9] was developed to study the permeation of hot noncondensable gases through porous media. Recent calculations using this code[10] show that less than 250 ft was the maximum extent of permeation through uncompacted, extremely permeable tuff (ρ_0 = 1.4, k = 2.2 darcys, porosity = 40 percent), using a realistic cavity pressure-cooling history for an 8-kt event buried 750 ft deep. When compaction and melting of the cavity wall are considered, venting through small interstices does not appear to be within the realm of possibility. Permeation of contaminants from a standing cavity through any path other then large diameter openings should never be a critical prompt-venting mechanism.

It is realized that this brief study of permeation does not establish the scientific fact that permeation through small tortuous paths could never occur in a particular event, but it does point to the extreme likelihood that other processes (e.g., gas acceleration) will be more critical and will thus control the establishment of burial criteria.

The role of faults in providing venting paths is not fully understood, and as a result has been of considerable concern. The surface expression of several vent paths (particularly the Pinstripe and Bandicoot Events) has been along planar features inferred to be faults. However, it is believed that the existence of a fault should not be considered prima facie cause for rejection of an emplacement site. Within the plastic region of deformation surrounding a nuclear explosion a fault should play no greater role in providing a vent path than is played by any other type of geologic contact. If the fault is simply a crack and no discontinuity of material properties exists across

its plane, the fault does not represent a reflecting surface; therefore, the resulting structure should be no different and present no more risk to venting than were the media not faulted. The case where gross heterogeneities exist across a fault or contact is discussed later in this report. The significance of geologic structure to venting is a subject for continuing research at the Lawrence Radiation Laboratory (LRL).

The possibility of late-time tensile openings around the cavity must be considered. Evidence of melt-filled openings extending radially from cavities (particularly in salt) has been observed. These cracks appear to originate at the cavity wall and to propagate radially outward. Cracks of this type could result from the interaction of rarefactions on the cavity, or from local tension relief associated with the late-time unloading of the material in the vicinity of the cavity. Regardless of their origin, these cracks have not been observed at a distance greater than 2 cavity radii from nuclear cavities. Significant permeation beyond this path that would lead to dynamic venting is not likely unless this crack communicates with an opening of another type such as a satellite hole.

A second type of tensile opening which may describe the Blanca Event can be visualized. This is the tensile opening which appears to propagate from the ground surface inward, but is not associated with spalling. Rinehart[11] explains that cracks of this type can result from the effects of surface shape. Figure 11 shows schematically the possible development of this type of opening for a shot placed in the side of a mesa. This type of opening may also develop if critically oriented internal material interfaces exist. It is in this context that faults may play a significant role in providing a vent path.

Late-Time Venting Mechanisms

During collapse two diametrical processes operate. As collapse progresses, cavity gases are displaced upward through newly exposed cold surfaces which tend to quench the gas. In the case where a subsidence crater is created, dynamic venting can occur by the displacement mechanism if the cavity gases being displaced have not cooled and condensed in the time required for the collapse to propagate to the surface. In the case where collapse does not reach the surface, dynamic venting should not occur unless there is an opening extending from the roof of the chimney to the

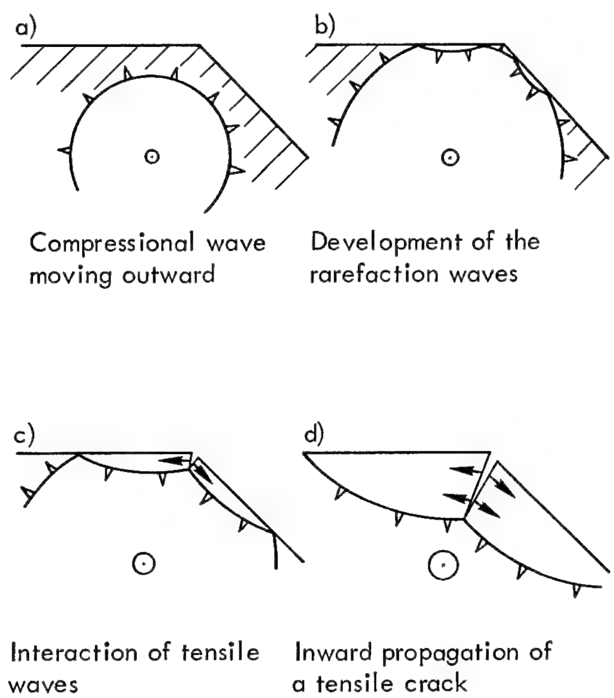

Fig. 11. Development of tensile crack in explosive event because of surface shape.

surface, as in the case where stemming used to close the emplacement hole falls into the chimney region, creating an opening to the surface.

Experimental evidence indicates that post-collapse mechanisms do not lead to dynamic venting. In nearly all events where prompt venting has occurred, collapse has been observed to be the termination of the dynamic venting phase. This termination is believed to result from the quenching process.

The central question is this: How much rubble exposed at the rate of collapse is required to quench the gas? A review of postshot drilling information has been initiated to determine the height to which contaminants have propagated into the chimney region of those events at NTS. A records search by Aron[12] has identified a number of events where the height of contaminants in the chimney is known to a reasonable degree of accuracy. From these values and the geometry of the chimney, the volume of contaminated rubble was computed. When an empirical approach is used, there appears to exist a crude relationship between the volume of contaminated rubble (the volume of rubble required to quench the gas) and the yield (Fig. 12). The relationship shown is the most conservative

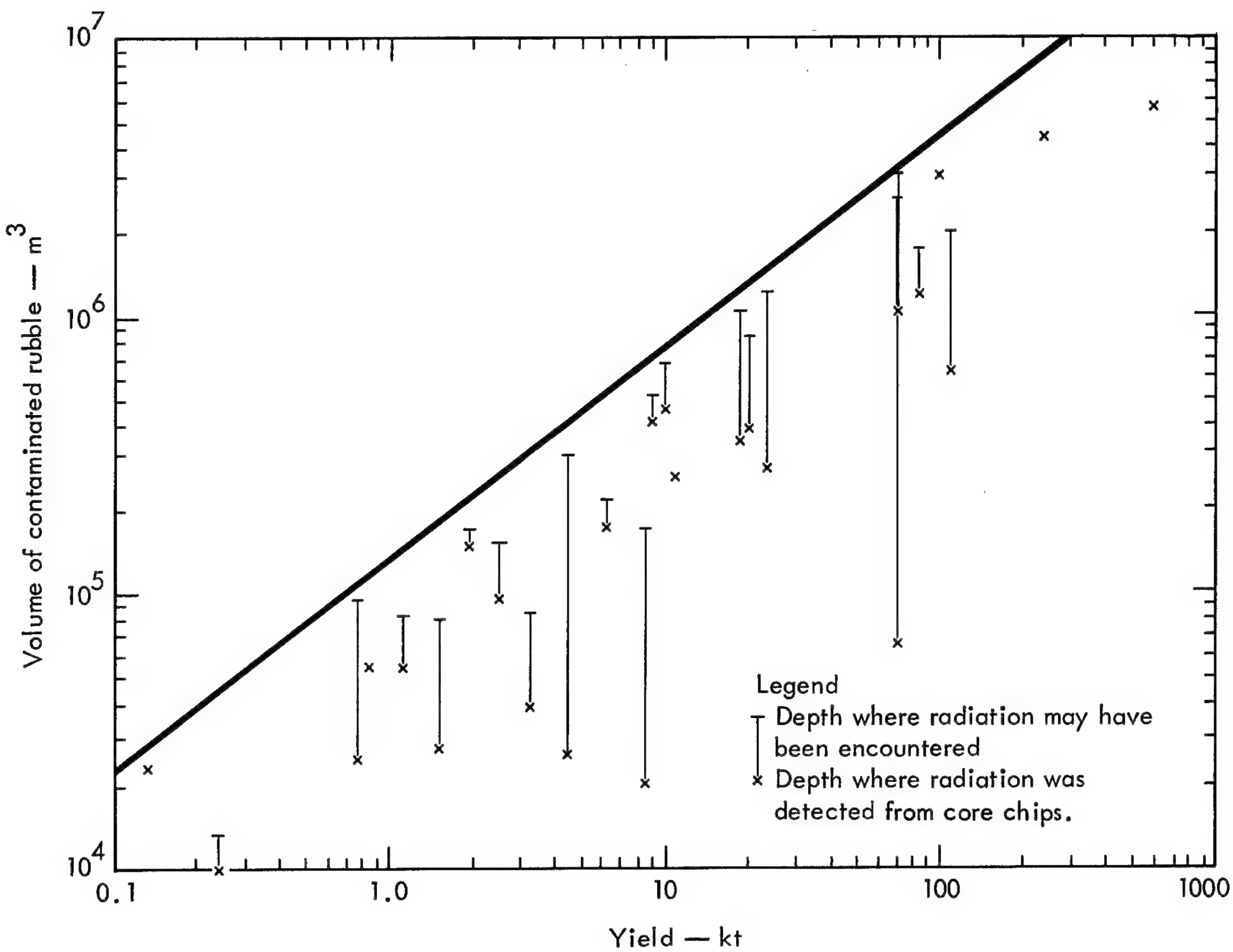

Fig. 12. Volume of contaminated rubble showing relationship between yield and volume of rubble required to quench the gas.

estimate of that experienced in silicate materials. This information translated into a depth vs yield relationship is shown in Fig. 13.

An analytical model for evaluating the opposing effects of the displacement and quenching processes is available. This model was initially proposed by Chapin.[13] Essentially it is a radiative and convective cooling model for calculating the late-time cavity pressure history which has been modified to allow for the addition of cold surfaces at the rate of collapse. In order to use this model at the present time, one must assume values for the cavity pressure conditions at the time of collapse, the average surface-area-to-volume ratio of the rubble, and the rate of chimney collapse. The significance of the model at this time is that it provides a first-principle approach to the problem and a basis for further investigation. Improvements can be made as more information becomes available. Programming this model is presently in progress under the direction of Chapin. Hand calculations have been made with this model to evaluate the possibilities of late-time venting in the Faultless Event. The comparison of the computed value for activity rise in the chimney, Aron's empirical value, and the measured value[14] was reasonably close for this stage of model development.

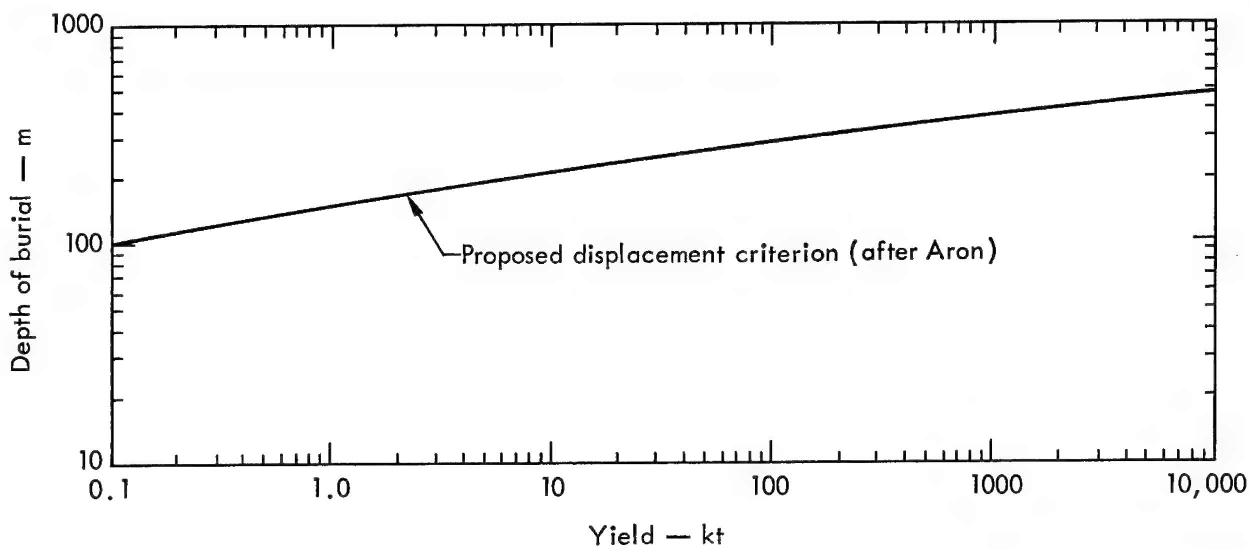

Fig. 13. Burial criterion based on volume of rubble required to quench the gas.

Evaluation of Present Empirical Criteria

The mechanisms which can lead to venting have been discussed. The processes that appear to be of primary concern in dynamic venting are (1) the so called "gas acceleration phase" of continued cavity growth, (2) energy flow through large diameter openings, and (3) upward displacement of cavity gases during chimney formation, or (4) combinations of these mechanisms.

In those events involving elaborate or extensive man-made openings, depth criteria have meaning only to insure that venting does not occur through the ground. The prevention of dynamic venting through these openings is solely dependent on the design and the construction of stemming and closure systems.

However, in most Plowshare underground applications elaborate openings are not required. The only openings existing are those around instrumentation and firing cables. Controlling possible venting through these openings is a relatively easy matter. For this reason the controlling mechanism in Plowshare underground applications appears to be either gas acceleration or the mechanisms associated with collapse. In these cases a criterion based on the mechanism controlling the particular event should be used. Figures 14 and 15 show the results of comparative studies for Lewis shale and Hardhat granite. These figures show the depth of burial required to prevent venting by (1) the gas acceleration mechanism and (2) the displacement mechanism. These relationships are then compared to the extrapolated criteria of 350 $W^{1/3}$. For Lewis shale the controlling mechanism above 6.5 kt appears to be gas acceleration. In Hardhat granite, gas acceleration controls throughout the range of yields shown. The difference in depth for containment with a gas acceleration criterion for a 1-Mt event in Lewis shale is approximately 300 m shallower than the extrapolated value from the $D = 350\ W^{1/3}$ criteria.

It must be reemphasized that the models with which we have evaluated venting are not new. These models have

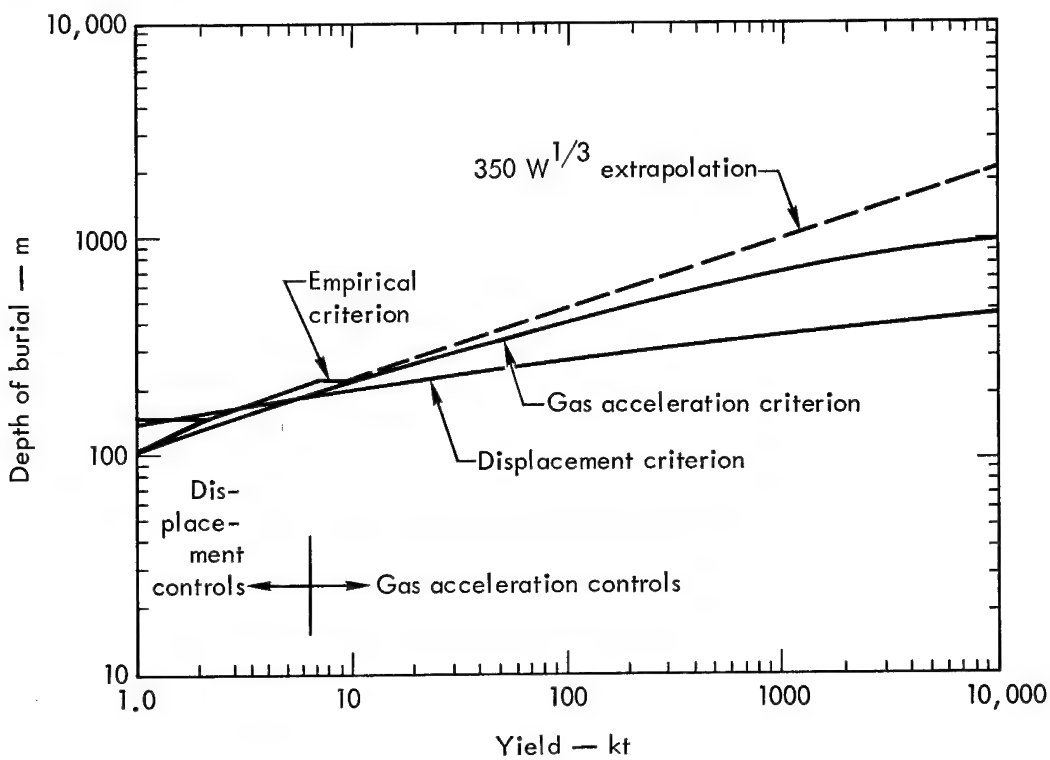

Fig. 14. Comparison of containment criteria (Lewis shale $\rho_0 = 2.61$).

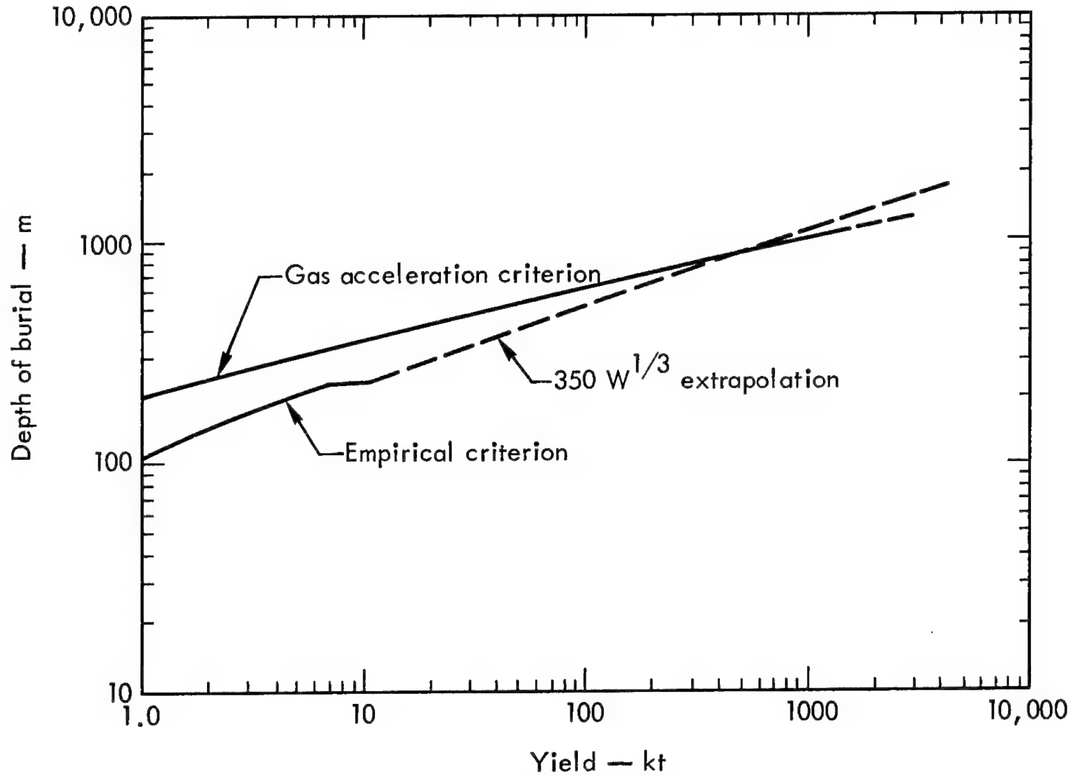

Fig. 15. Comparison of containment criteria (Hardhat granite $\rho_0 = 2.67$).

been developed over the past ten years through Plowshare research[15] and have been verified by full-scale nuclear tests on both sides of the line: cratering experiments (designed to vent) and contained experiments. Thus the use of these models in evaluating the depth for a given yield and geologic environment to achieve containment falls within the realm of experience necessary to be applied by any governing body supervising or overseeing nuclear safety.

We believe that a gas acceleration model should be used in establishing minimum burial requirements for all nuclear applications where containment of dynamic vent is a necessity. Although the implementation of this model requires a substantial equation-of-state and calculational effort, these models provide a logical basis for establishing burial depths which assure that dynamic venting through the ground will not occur.

Maximum Credible Vent

Up to this point we have discussed dynamic venting mechanisms and criteria for their prevention. There remains the problem of seepage of contaminants to the surface. This seepage is caused by gas diffusion, percolation, and flow through small man-made openings (cable openings, casing separations, etc.). It appears that the possibility of these occurrences can never be completely precluded; there

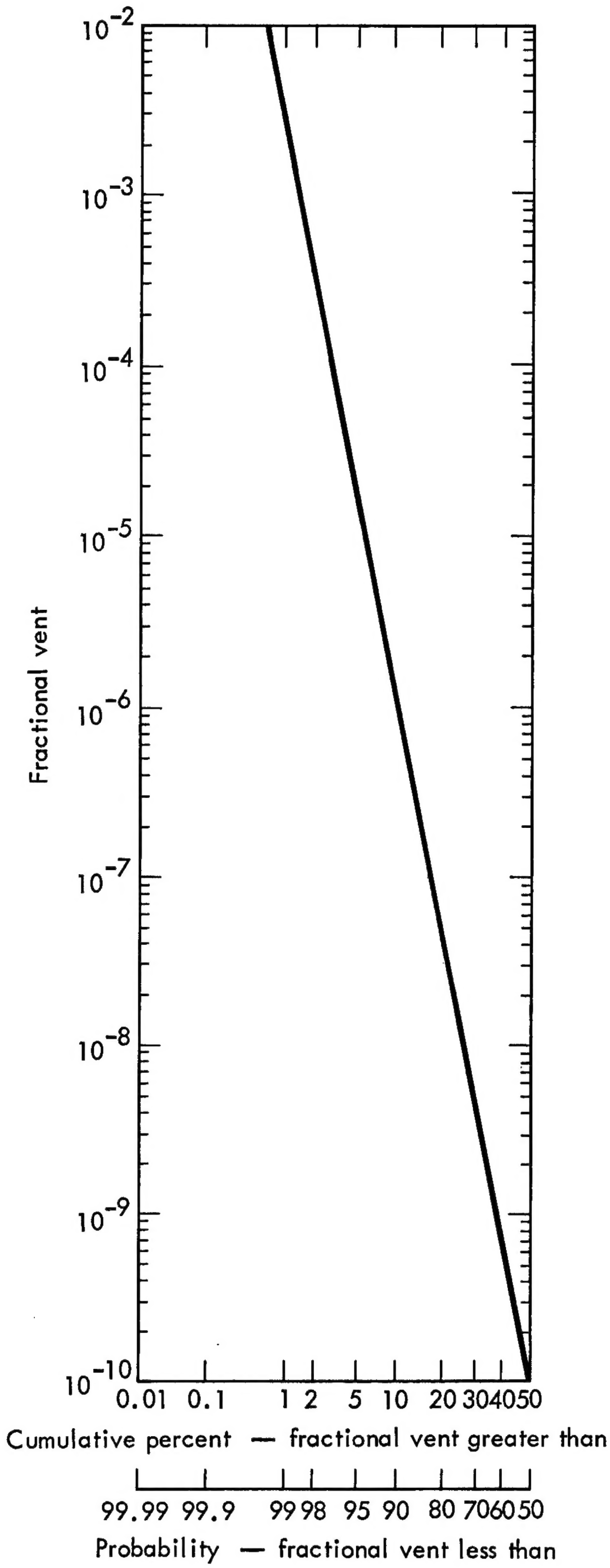

Fig. 16. Probability of radioactive release from stemmed drill holes.

is always some chance that contaminants will reach the surface. Two questions: What quantity can be expected? and Is this quantity acceptable? The nature of the questions infers a statistical answer.

With regard to gas diffusion, the data are insufficient for statistical analysis. Only two events have been identified where seepage due to gas diffusion occurred. These events were in dolomite where quantities of noncondensable CO_2 were generated. The maximum release observed was 6.9×10^4 Ci corrected to a standard time of H + 12 hr. Seepage to the surface with ground water (percolation) is a function of time and flow conditions. Each location must be evaluated on its own merits to determine what danger, if any, exists to public health.

Finally, we consider seepage through cable openings. A survey was made of venting occurrences in order to determine the radiation hazard from these openings. The survey included all LRL nuclear experiments detonated in stemmed vertical drill holes during the period 15 September 1961 to the present. The review identified those events where dynamic venting was precluded. One fourth of the events in this sample (which excludes dynamic venting) produced seepage in detectable quantities.

Figure 16 shows the log normal distribution which best fits the data from the above sample. The fractional vent is the amount of vented radioactive material observed divided by the quantity produced by the event. This measure makes the result somewhat independent of device design and yield. The figure shows that 99 percent of the time the fractional vent due to seepage through

cable openings and other small openings associated with a fully stemmed emplacement hole will be less than 3×10^{-3}. Expressed another way this seepage would be 0.3 percent of the release had the device been fired at the surface. For a device with a fission yield of 2 kt the probability is 99 percent that the seepage will release less than 7.4×10^4 Ci at H + 12 hr.* The probability is 90 percent that the release will be only 22 Ci at H + 12 hr. Finally, there is a 75 percent chance that contaminants never reach the surface in detectable quantities.

*1-kt fission decays to 1.32×10^7 Ci in 10 hr.

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